

# Deep census of variable stars in a VLT/VIMOS field in Carina<sup>★</sup>

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## ABSTRACT

We have searched for variable stars in deep V-band images of a field towards the Galactic plane in Carina. The images were taken with VIMOS instrument at ESO VLT during 4 contiguous nights in April 2005. We detected 348 variables among 50897 stars in the magnitude range between  $V = 15.4$  and  $V = 24.5$  mag. Upon detection, we classified the variables by direct eye inspection of their light curves. All variable objects but 9 OGLE transits in the field are new discoveries. We provide a complete catalog of all variables which includes eclipsing/ellipsoidal binaries, miscellaneous pulsators (mostly  $\delta$  Scuti-type variables), stars with flares and other (irregular and likely long-period) variables. Only two of the stars in our sample are known to host planets. Our result give some implications for future large variability surveys.

**Key words.** Stars: variables: general – variables: delta Sct – binaries: eclipsing – Stars: flare – planetary systems – Stars: statistics

## 1. Introduction

Variable stars provide important information on the nature and evolution of stars in various regions of our Galaxy. Eclipsing binary stars give us information on the masses and radii of stars (see e.g. Huang & Struve, 1956; Popper, 1985). For some, i.e. the detached systems, it is possible to measure distances (Paczynski, 1997), which is particularly useful in case of star clusters (see e.g. Bonanos et al., 2006; Kaluzny et al., 2007). Pulsating variables, such as Cepheids and RR Lyrae, serve as such distance indicators (e.g. Benedict et al., 2007; Feast et al., 2008). The type of pulsators known as  $\delta$  Scuti stars offer a unique insight into the internal structure and evolution of main-sequence objects (Thompson et al., 2003; Goupil et al., 2005).

Due to the advent of large-scale wide-field photometric surveys the number of new variables has increased rapidly. The surveys are usually dedicated to the detection of particular objects, like transiting extrasolar planets, microlensing events or gamma ray burst afterglows, e.g. MACHO (Alcock et al., 2000) and OGLE surveys (Udalski et al., 2003). Most of the wide-field surveys are conducted with small (less than 0.5 m) robotic telescopes, e.g. ASAS (All-Sky Automated Survey, Pojmański, 2001), ROTSE (Robotic Optical Transient Search Experiment, Woźniak, 2004), allowing the search for variability only for bright stars (down to  $\sim 15$  mag in the V band). Until re-

cently the big telescopes, i.e. those of 4-10 meters in diameter, have been focusing rather on individual objects, due to their small fields of view. Practically there have been very few long and deep variability surveys. In this paper we present the results of searches for variable objects in a deep (down to  $V \approx 24.5$  mag) galactic field in the constellation of Carina, based on data collected with an 8-m telescope for 4 continuous nights. Our results show the great potential of upcoming large visual and near-infrared surveys, like LSST (Large Synoptic Survey Telescope, Ivezić et al., 2008), VVV (Vista Variables in Via Lactea, Ahumada & Minniti, 2006) or Pan-STARRS (Kaiser et al., 2002).

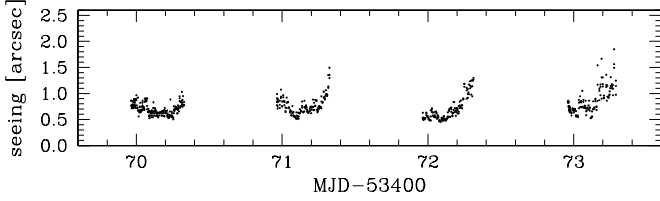
## 2. Observations and data reduction

Observations were carried out with VIMOS at the Unit Telescope 3 (UT3) of the European Southern Observatory Very Large Telescope (ESO VLT) located at Paranal Observatory from April 9 to 12, 2009. VIMOS is an imager and multi-object spectrograph (LeFevre et al., 2003). Its field of view consists of 4 quadrants of about  $7' \times 8'$  each, separated by a cross,  $2'$  wide. The CCD size is  $2048 \times 2440$  pixels with a pixel size of  $0''.205$ .

The main goal of the program was to photometrically follow-up of over 30 OGLE transiting candidates. Some individual results have been published by Fernández et al. (2006), Díaz et al. (2007), Hoyer et al. (2007), Minniti et al. (2007), Díaz et al. (2008), Pietrukowicz et al. (2009). The field analyzed in this paper is one out of four VIMOS fields monitored during the run, and is the only one which was observed during 4 full nights. Equatorial coordinates of the center of the

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<sup>★</sup> Based on observations collected with the Very Large Telescope at Paranal Observatory (ESO Programme 075.C-0427(A), DM and JMF visiting observers).



**Fig. 1.** The seeing during the four observing nights.

field are  $RA(2000.0)=10^h52^m56^s$ ,  $Dec(2000.0)=-61^\circ28'15''$  or  $l = 289.269$ ,  $b = -1.783$ . The field contains 9 OGLE transits, two of which were confirmed to be caused by planets: OGLE-TR-111b (Pont et al., 2004) and OGLE-TR-113b (Bouchy et al., 2004; Konacki et al., 2004). All 4 nights were clear throughout, with sub-arcsecond seeing during most of the time (see Fig. 1). The dataset consists of 660 images taken only in the  $V$ -band.

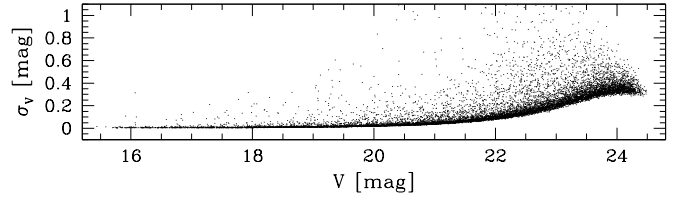
The periphery of each quadrant suffers from coma. Therefore, for our analysis we cut out a slightly smaller area of  $1900 \times 2100$  pixels, covering  $7'.18 \times 6'.49$ . The total field in which we searched for variable objects equals  $186.3 \text{ arcmin}^2$ .

The photometry was extracted with the help of the *Difference Image Analysis Package* (DIAPL) written by Woźniak (2000) and recently modified by W. Pych<sup>1</sup>. The package is an implementation of a method developed by Alard & Lupton (1998). To obtain better quality of photometry we divided the field into  $475 \times 525$  pixel subfields.

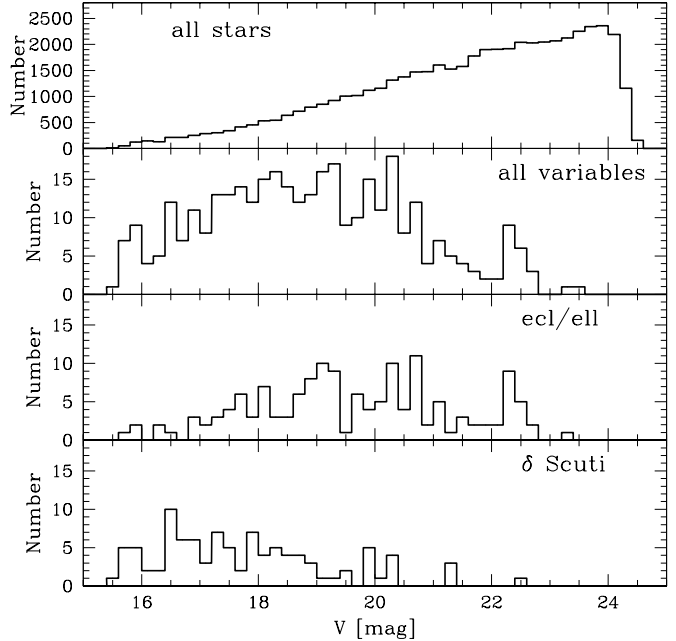
Reference frames were constructed by combining the 8 or the 9 best individual images (depending on the quadrant). The profile photometry for the reference frame was extracted with DAOPHOT/ALLSTAR (Stetson, 1987). These measurements were used to transform the light curves from differential flux units into instrumental magnitudes, which were later transformed to the standard  $V$ -band magnitudes by adding an offset derived from  $V$ -band magnitudes of the planetary transits located in the field (Díaz et al., 2007; Minniti et al., 2007). The quality of the photometry is illustrated in Fig. 2. In this figure we plot the standard deviation vs. the average magnitude for stars from one of the VIMOS quadrants.

Due to the short period of the observations we decided to look for variables initially by direct eye inspection of all 50897 light curves. This lasted about one week. For comparison and more reliable statistics, we performed an independent period search with the TATRY code (see Schwarzenberg-Czerny, 1989, 1996). After the automatic search we sorted all stars by decreasing variability (quality) factor, which is generated by the code, and we looked at the most promising light curves. The total number of detected variables reached 348 objects. Interestingly, among 175 periodic variables except  $\delta$  Scuti stars only four additional variables were found, and up to 51 variables were missed as the result of the automatic search in comparison to the by-eye method. The missing objects were mostly faint ( $V > 19 \text{ mag}$ ) low-amplitude ( $\Delta V < 0.15 \text{ mag}$ ) stars. However, some of them could be missed due to the cut of the list of stars for revision.

Finally, all detected variables were sorted by increasing right ascension and classified by looking at the shape of the light curves and possible periods.



**Fig. 2.** The photometric errors for 12571 stars from the VIMOS quadrant A2 plotted as a function of  $V$  magnitude.



**Fig. 3.** Magnitude distribution of all analysed stars (50897 objects), all detected variables in the sample (348 objects), all stars classified as eclipsing/ellipsoidal binaries (148 objects) and all  $\delta$  Scuti stars (99 objects). The bin size is 0.2 mag.

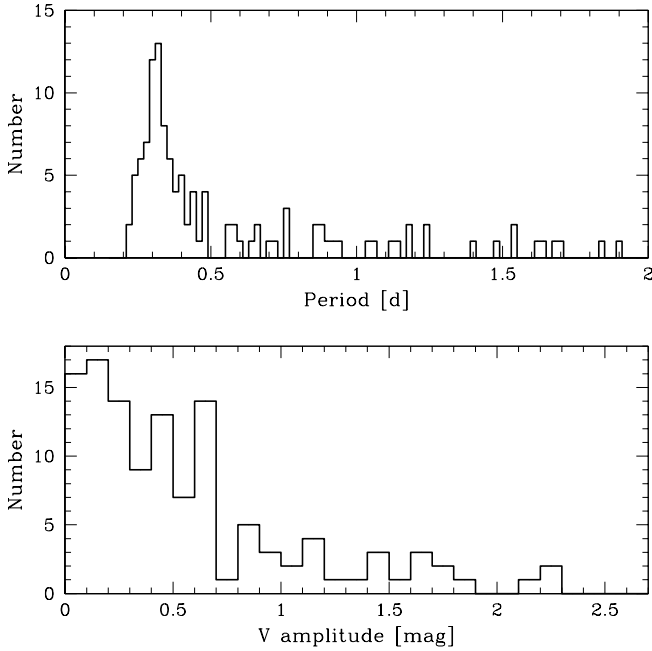
### 3. The variables

Figure 3 shows four histograms representing magnitude distributions for all stars, all variables, eclipsing/ellipsoidal binaries and  $\delta$  Scuti stars, respectively. The distribution for the complete sample of variable stars peaks at  $V \approx 18.5 \text{ mag}$ . The number of eclipsing/ellipsoidal variables starts to decrease below approximately  $V = 19.5 \text{ mag}$ , but still many faint objects of this type were detected thanks to their high amplitudes. For  $\delta$  Scuti stars, which have typical amplitudes of 0.02-0.06 mag, the detection efficiency seems to peak at  $V \approx 17 \text{ mag}$ . Very few stars of this type were found to be fainter than  $V = 20 \text{ mag}$ .

#### 3.1. Eclipsing variables

In Fig. 4 we show the period and amplitude distributions for eclipsing/ellipsoidal binaries. The distribution for the shortest periods could be fit by a Gaussian with a mean period of 0.31 d. This value differs slightly from the mean value of 0.277 d and  $\sigma = 0.036 \text{ d}$ , as found by Wiedrahe & Bayliss (2008) in a Galactic plane field in Lupus, and the value of 0.37 d derived from ASAS data (Paczynski et al., 2006). From the amplitude

<sup>1</sup> The package is available at <http://users.camk.edu.pl/pych/DIAPL/>



**Fig. 4.** Period distribution (upper panel) and amplitude distribution (lower panel) for eclipsing binaries with estimated period.

distribution we conclude that about three fourths of the sample binaries have  $V$  amplitudes below 0.7 mag.

The following figures, Figs. 5-7, illustrate phased light curves for all 121 eclipsing/ellipsoidal variables, for which we were able to derive accurate periods. Note that the faintest eclipsing variable found in our data, V050, has the maximum brightness of about 23.3 mag and the amplitude of  $\approx 1.4$  mag in  $V$ . System V009 has the largest amplitude of 2.23 mag. Variable V149 shows short and shallow eclipses besides the sinusoidal changes in its brightness. It may be an RS CVn binary, but more data is needed to answer the question what kind of object this is. Variable V278 corresponds the transit OGLE-TR-109 phased with the transiting period of 0.589127 d. The analysis of these photometric data by Fernández et al. (2006), combined with high-resolution spectroscopic data by Pont et al. (2005), leaves the nature of the object unclear. Two scenarios are possible: OGLE-TR-109 can be either a blend of the star with a background eclipsing binary or a transiting planet (less likely because of its very short period).

In Fig. 8 we present the light curves of stars showing one or two eclipses, but for which the time-span of our observations was not sufficient to estimate the period. Some variables in this sample need further explanation. Star V314 is known as the transit OGLE-TR-106 with a period of 2.53585 days (Udalski et al., 2002). Pont et al. (2005) show that this object is not a transiting planet but an eclipsing binary where one of the companions is a low mass M dwarf with  $0.116 \pm 0.021 M_{\odot}$ .

Object V041 changed its brightness by about 0.25 mag showing an unexpected flat-bottom eclipse during the second night. This eclipse lasted about 4.5 hours, had an amplitude of  $\sim 0.05$  mag, and suggests a periodicity in the object. The overall shape of the light curve indicates a periodic behavior, too. Based on the incomplete photometric data we can only speculate about the nature of the variable by asking several questions. Is this object an eclipsing binary containing a pulsating star as the primary or is it just a blend? Was the observed eclipse a tran-

sit of a planetary/low-luminosity object or the secondary eclipse in a binary system? If it is indeed a real binary, what are the parameters of the components? More data are needed to find the answers in this very interesting case.

The light curve of eclipsing variable V224 features some kind of bumps occurring regularly at the end of every night. The bumps are caused by the diffraction spikes of a nearby saturated star.

### 3.2. Pulsating variables

We classified 99 stars as  $\delta$  Scuti type pulsators. Their light curves are shown in Figs. 9-11. The amplitudes of all the stars except V340 are in the range between 0.015 and 0.230 mag. The variable V340 has an exceptionally large amplitude of about 1.0 mag. We do not attempt to derive exact periods, since most of the stars are multiperiodic variables, and hence require more sophisticated analysis, which will be subject of future studies.

Other pulsating variables are shown in Figs. 12-13. The periods of the variables range between 0.2307 and 4.1527 days. Variables V010, V018, V038, V049, V086, V098, V102, V160, V222, V251 and V342 are good candidates for RR Lyrae stars, whereas variables V012, V090, V231 and V339 are likely distant Cepheids. Light curves of miscellaneous variables are shown in Fig. 14. For example, variables V017, V029, V030, V128, V233, V241, V302 are good long-period candidates.

### 3.3. Stars with flares and planetary transits

Light curves of seven stars with flares are shown in Fig. 15. Table 1 summaries photometric information on these stars. The amplitudes of flares in the cases of V007 and V094 are larger than 2.0 mag, while in the other five cases they are smaller than 1.0 mag. The fading part of the flare in V294 shows a kind of knee. Star V033 is periodic, with  $P = 1.1625$  d (the phased light curve is shown in Fig. 12).

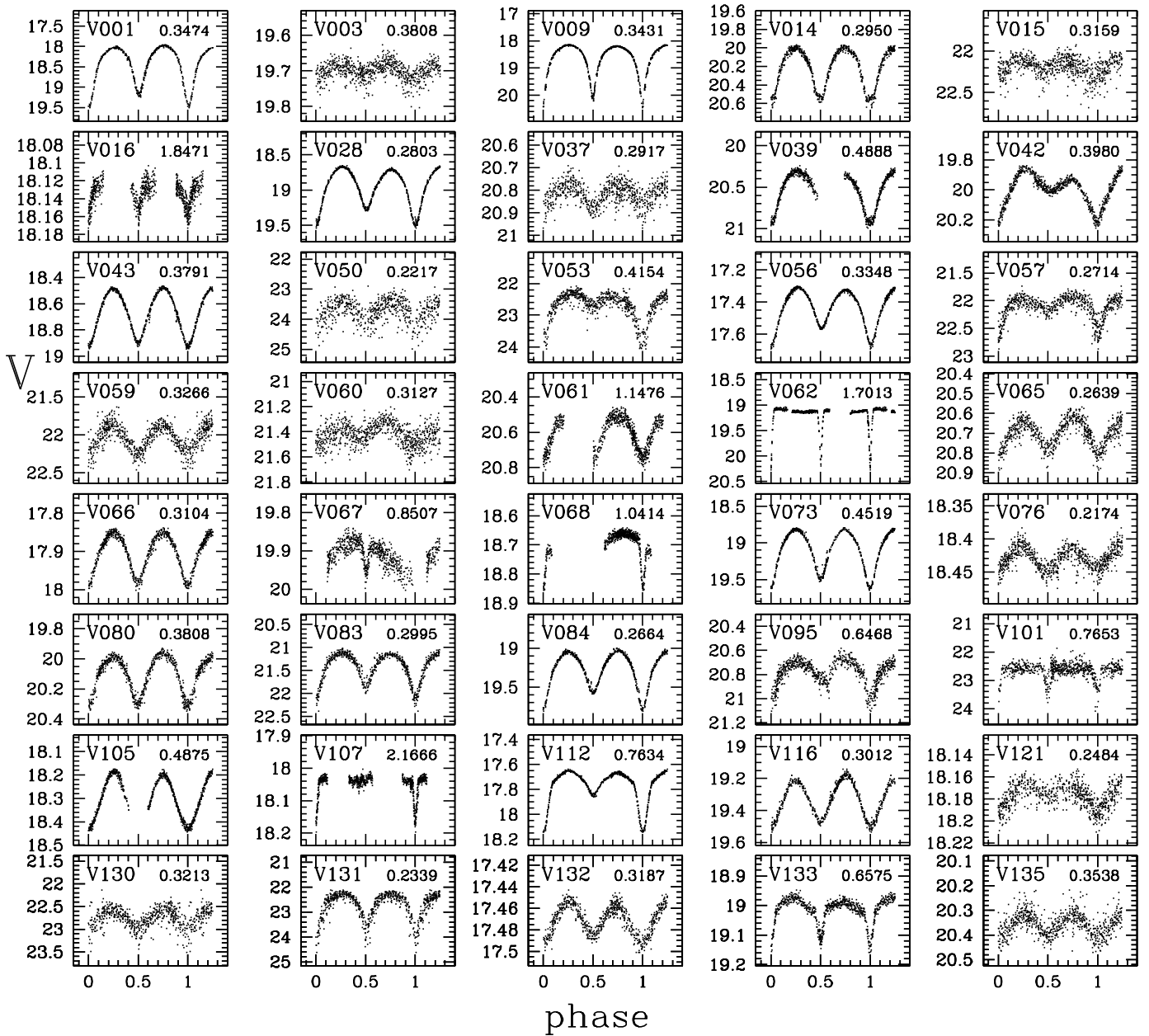
**Table 1.** Photometric information on flares detected in seven stars.

Star	$V$ [mag]	$\Delta V$ [mag]	Duration [h:m]	Remarks
V006	17.95	0.33	1:40	
V007	22.70	2.90	1:35	
V033	19.32	0.20	0:55	periodic, $P = 1.1625$ d
V082	19.47	0.15	0:55	
V094	23.50	2.20	1:55	
V261	19.75	0.13	0:55	
V294	19.92	0.62	2:50	

Finally, Fig. 16, presents our own photometry of two planetary transits: OGLE-TR-111 (Pont et al., 2004) and OGLE-TR-113 (Bouchy et al., 2004). Both of them are caused by hot Jupiters. Details on the photometry of the transits we give in Pietrukowicz et al. (2009).

## 4. Conclusions

The search for variable objects in the VIMOS field towards the Galactic plane in Carina resulted in the detection of 348 variables among 50897 stars down to  $V = 24.5$  mag. Only five of the objects were previously known to be variable. These were OGLE



**Fig. 5.** Light curves for eclipsing or ellipsoidal variables with estimated periods (part 1 of 3). The identifications and periods in days are given for each object.

transits TR-106, TR-109, TR-110, TR-111 and TR-113. The last two transits were confirmed to be caused by hot Jupiters, while the first three seem to be binary stars. We note that four other OGLE objects lie in the same field (TR-105, TR-108, TR-114, TR-198), but no variability was detected for them during our observations. Table 2 gives statistical information on the variables found. All photometric data, finding charts and a large table with equatorial coordinates, periods, magnitudes and amplitudes of the variables are available on the Internet at

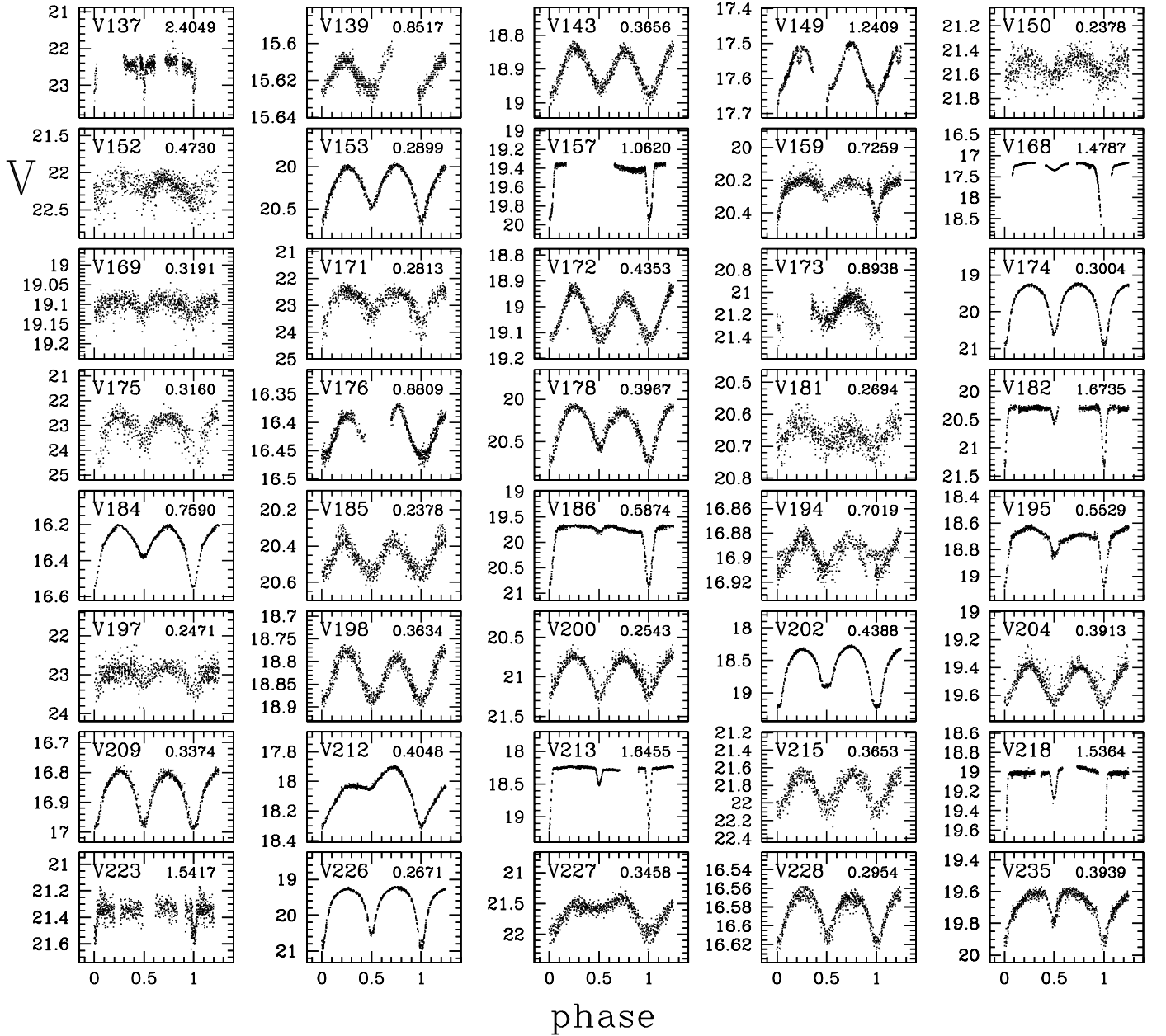
<ftp://ftp.astro.puc.cl/pub/pietruk/VIMOSvar/>

About half of the detected variables are eclipsing/ellipsoidal binaries, while the other half are pulsating variables of different types, mostly  $\delta$  Scuti stars. Based on the numbers in Table 2 one can say that about seven stars per 1000 show detectable

brightness variations. On average, three of them are eclipsing/ellipsoidal binaries, three are pulsating variables (where two are usually  $\delta$  Scuti stars). Other variable objects in the sample show changes on longer time-scales (more than 4 days) or represent transient events (stars with flares and transits).

We stress that the VIMOS observations lasted only 4 nights and therefore we were not able to detect variable objects with longer time scales. Long periods are often present in red giants, which are bright and easily detectable.

There has not been any other such deep and of similar time-span and time-resolution variability survey so far from the ground. However, we can compare with other two long-term but shallower ground-based surveys recently published. For example, Weldrake & Bayliss (2008) found 494 variables in the sample of 110 372 stars in Lupus, what gives  $\sim 0.45\%$ . The percent-



**Fig. 6.** Light curves for eclipsing or ellipsoidal variables with estimated periods (part 2 of 3).

age of detected variables in the ASAS survey (Paczynski et al., 2006) is only 0.29%. There, among 17 000 000 stars 50 099 were found to change their brightness. The percentage of variables detected in our work,  $\sim 0.69\%$  of all the stars in the sample, is much higher than in the two surveys. Also, one has to remember that this is only a lower limit for the variable detection. A deep Hubble Space Telescope survey dedicated to find planetary transits was carried out by Sahu et al. (2006). Such database would sample faint variables in the Galactic bulge, useful for comparison with the present work.

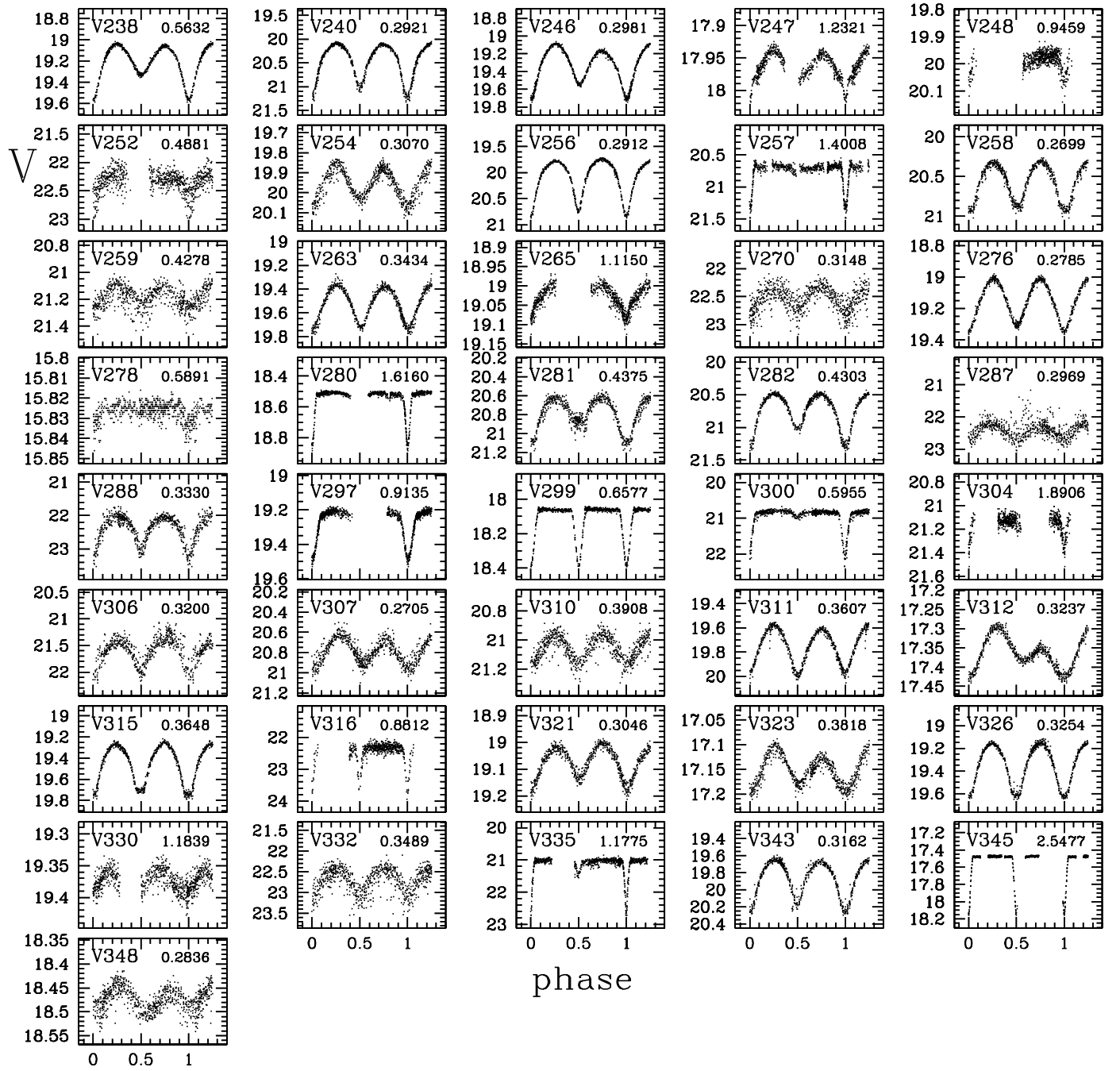
We decided to search for variables by eye initially just due to the short period of the VIMOS observations. It is obvious that this method will not be efficient in case of hundreds of thousands of stars monitored for hundreds of nights. Our variable star search was later automated, yielding similar results. The present results, including the large number of newly de-

tected variables of different types in a limited field, high quality photometry, high accuracy of the determined periods, show that ground-based wide-field variability surveys are powerful tool to draw a more detailed picture of our Galaxy.

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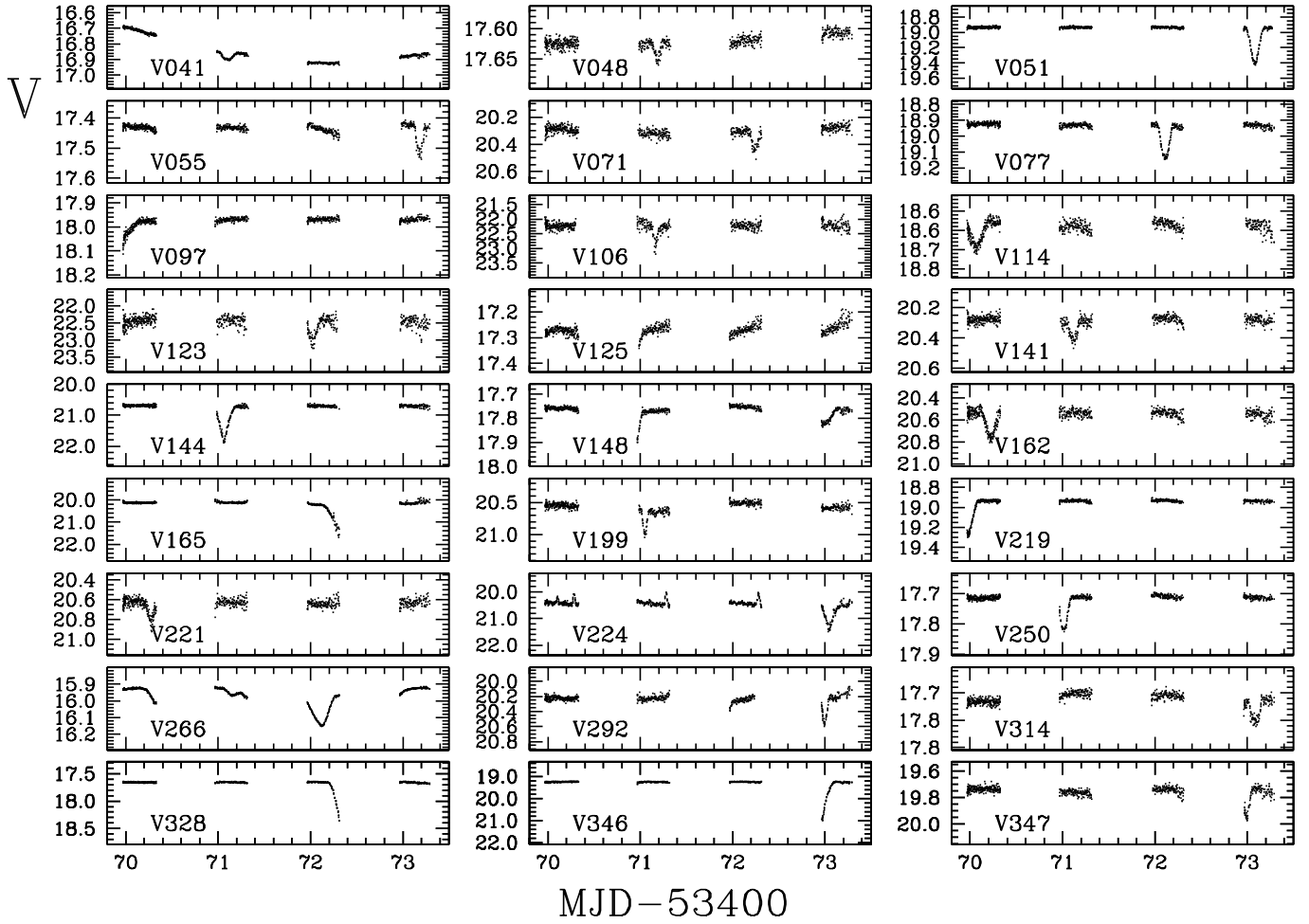
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**Fig. 7.** Light curves for eclipsing or ellipsoidal variables with estimated periods (part 3 of 3). Note that the object V278 is the OGLE transit TR-109 phased with transiting period of 0.589127 d.

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**Fig. 8.** Light curves for other eclipsing variables. Note that the object V314 is the OGLE transit TR-106 with an M dwarf star as a component.

**Table 2.** Number of variables of different types found in the data.

Type of stars	Number	Percentage
All stars searched for variability	50897	100 %
All known variables in the field	352	0.692 %
All variables detected in our survey	348	0.684 %
All eclipsing	148	0.291 %
Eclipsing with known period	121	
Other eclipsing	27	
Pulsating variables	153	0.301 %
$\delta$ Scuti	99	0.195 %
Other pulsating	54	
Other variables	39	
Stars with flares	7	0.014 %
Planetary transits	2	0.004 %
Variables not detected (OGLE transits)	4	

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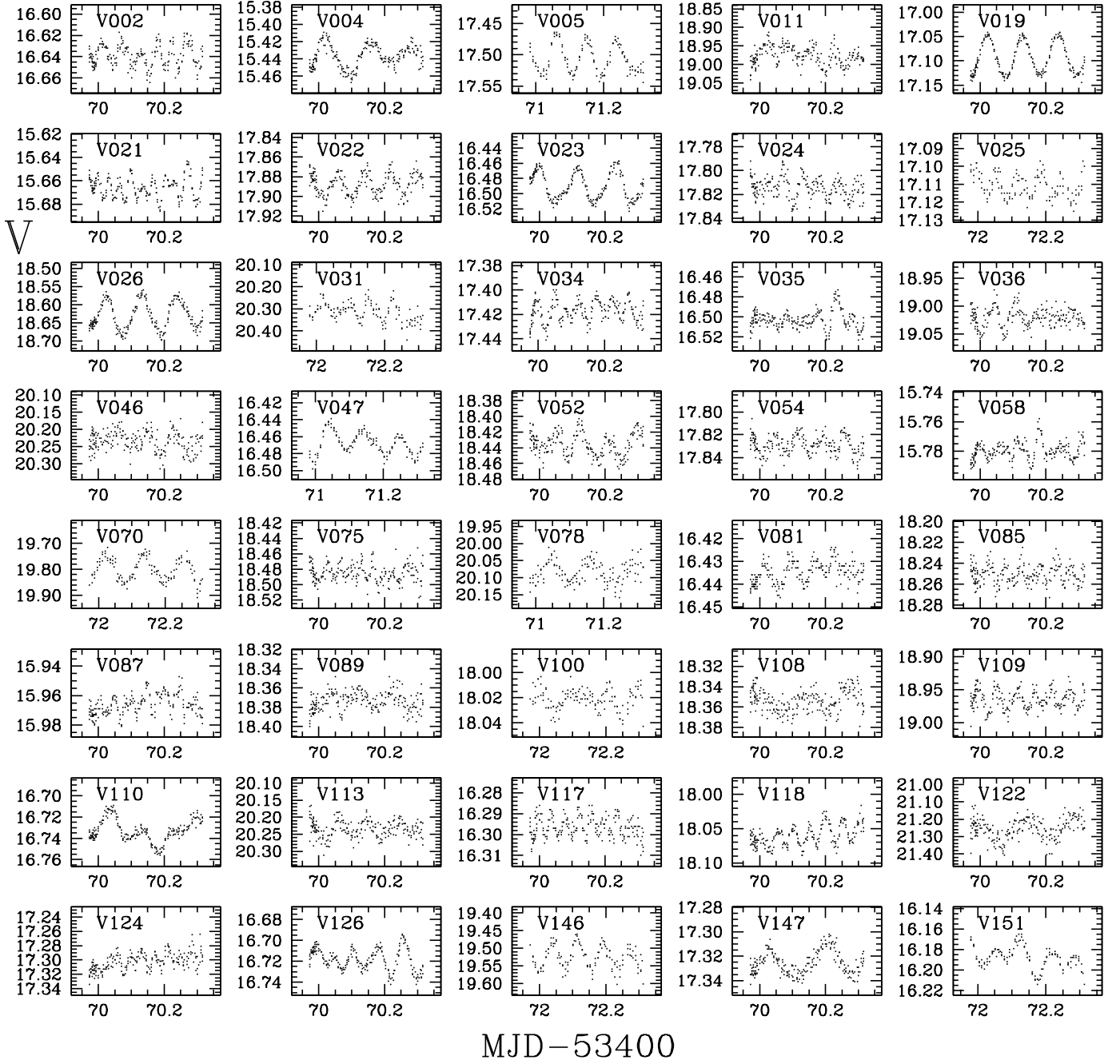
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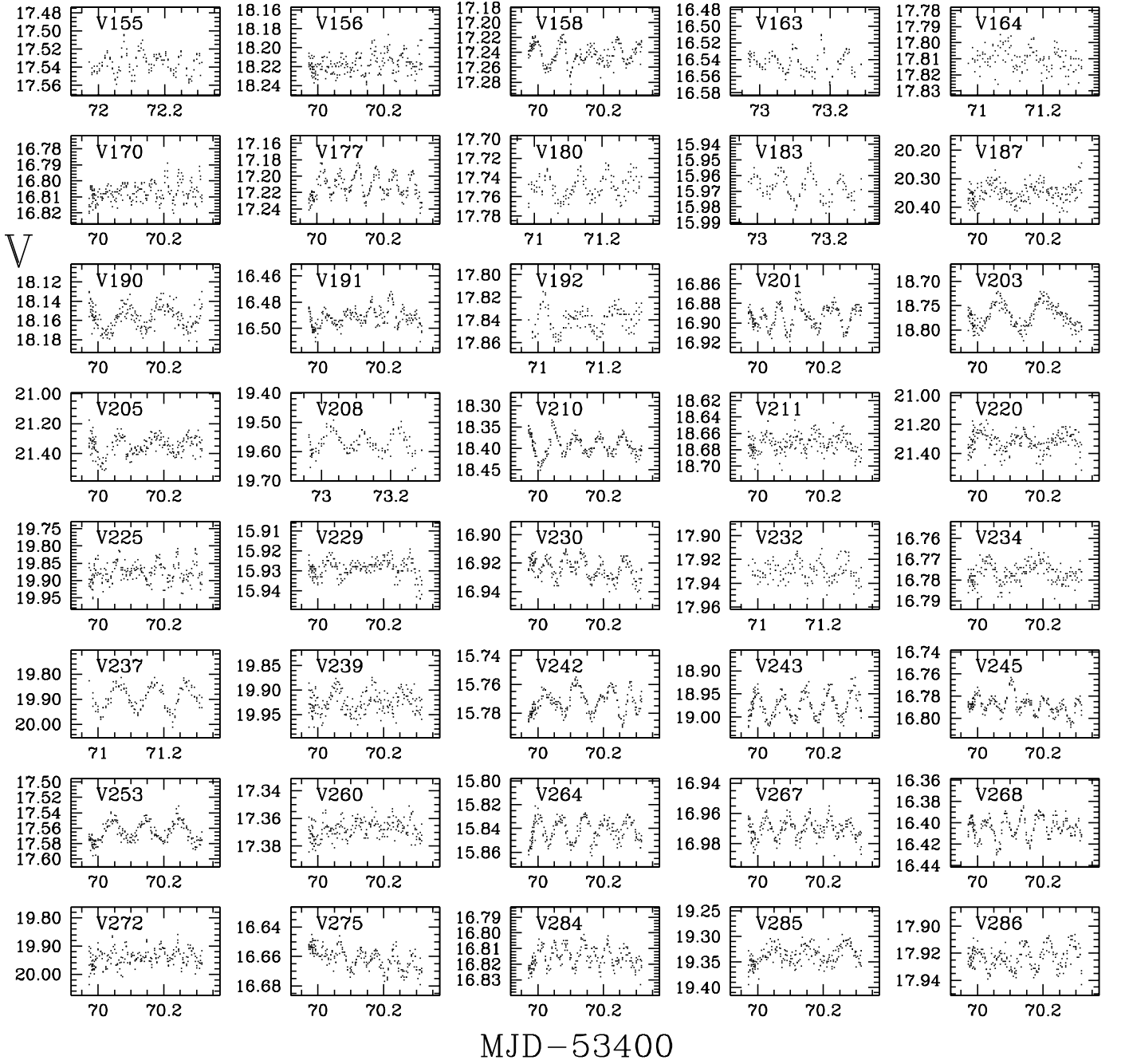
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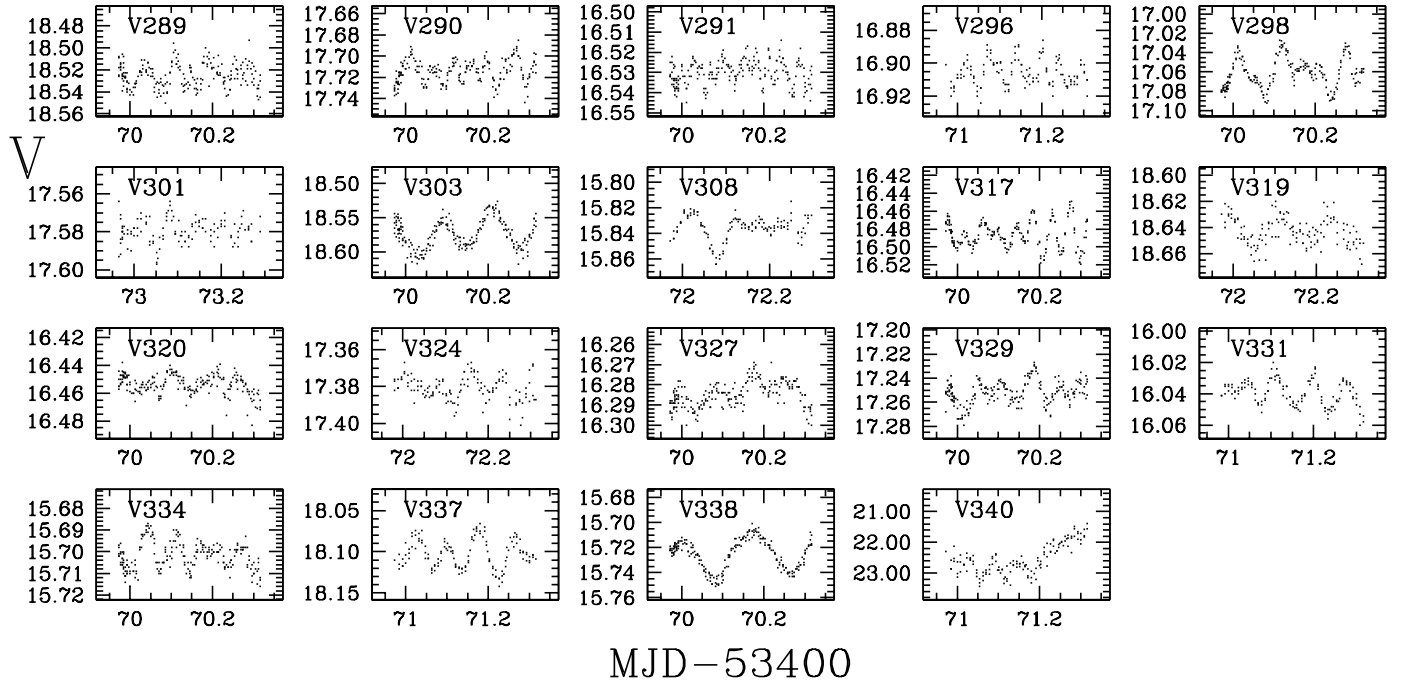


**Fig. 9.** Light curves for detected  $\delta$  Scuti-type variables (part 1 of 3). Each panel presents only data points from a single night.

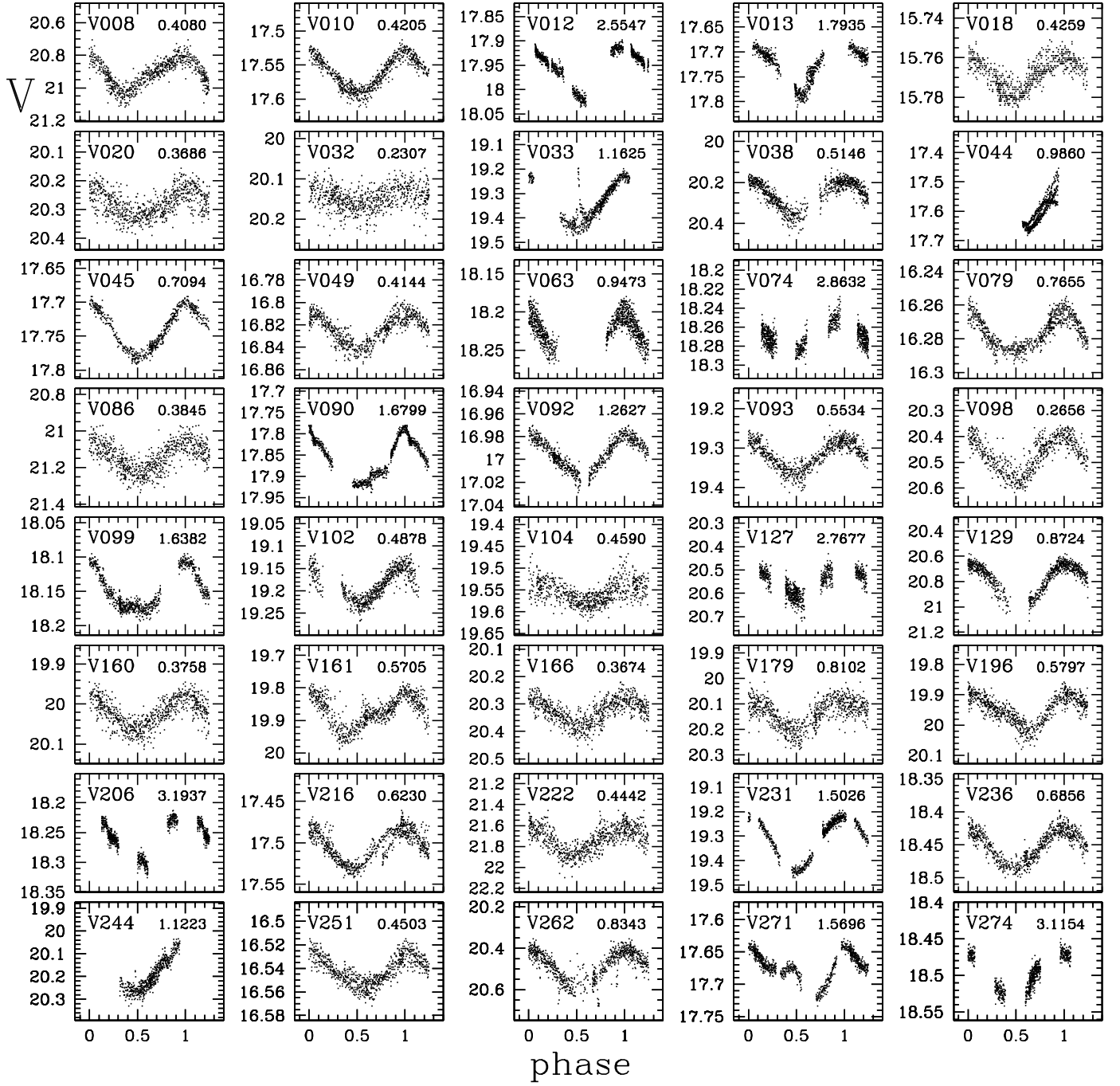




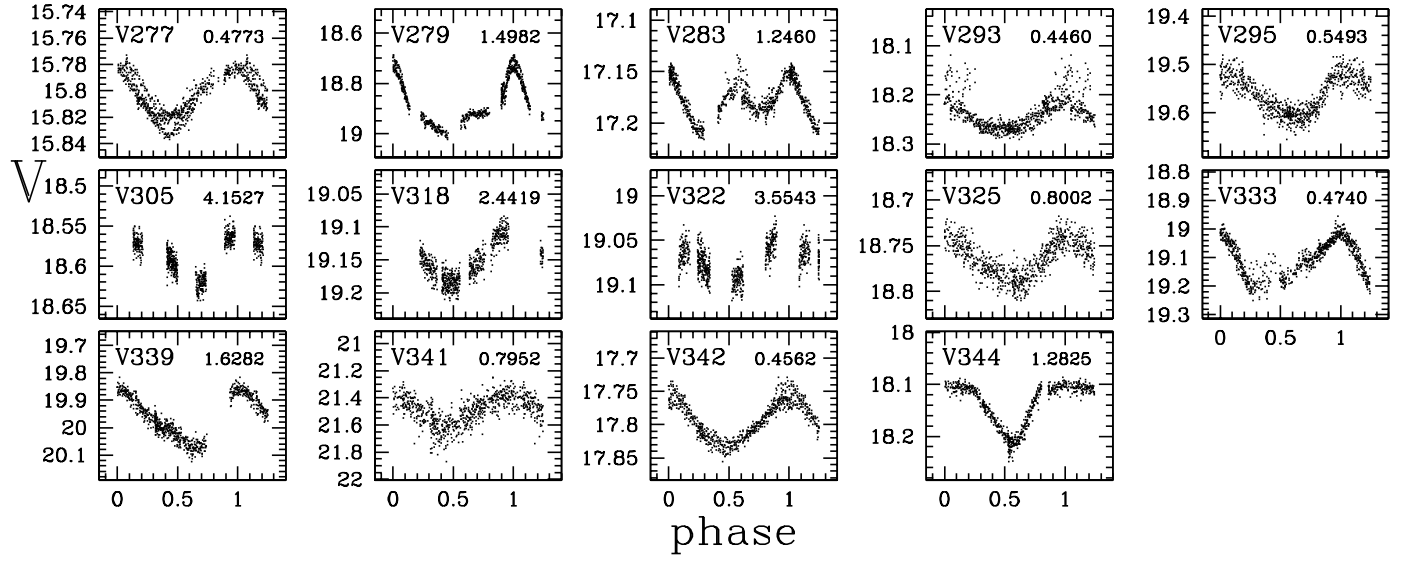
**Fig. 10.** Light curves for detected  $\delta$  Scuti-type variables (part 2 of 3).



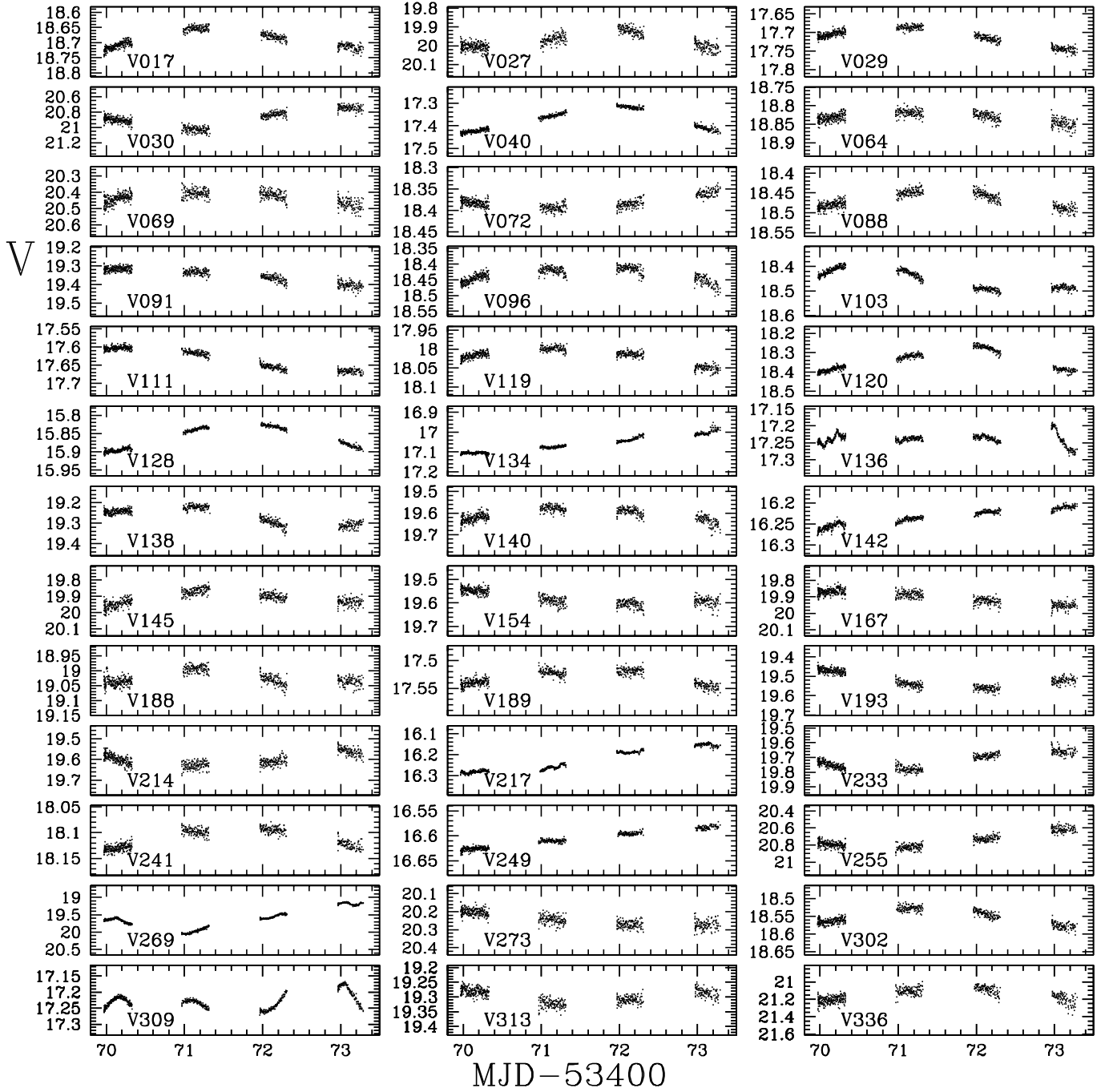
**Fig. 11.** Light curves for detected  $\delta$  Scuti-type variables (part 3 of 3).



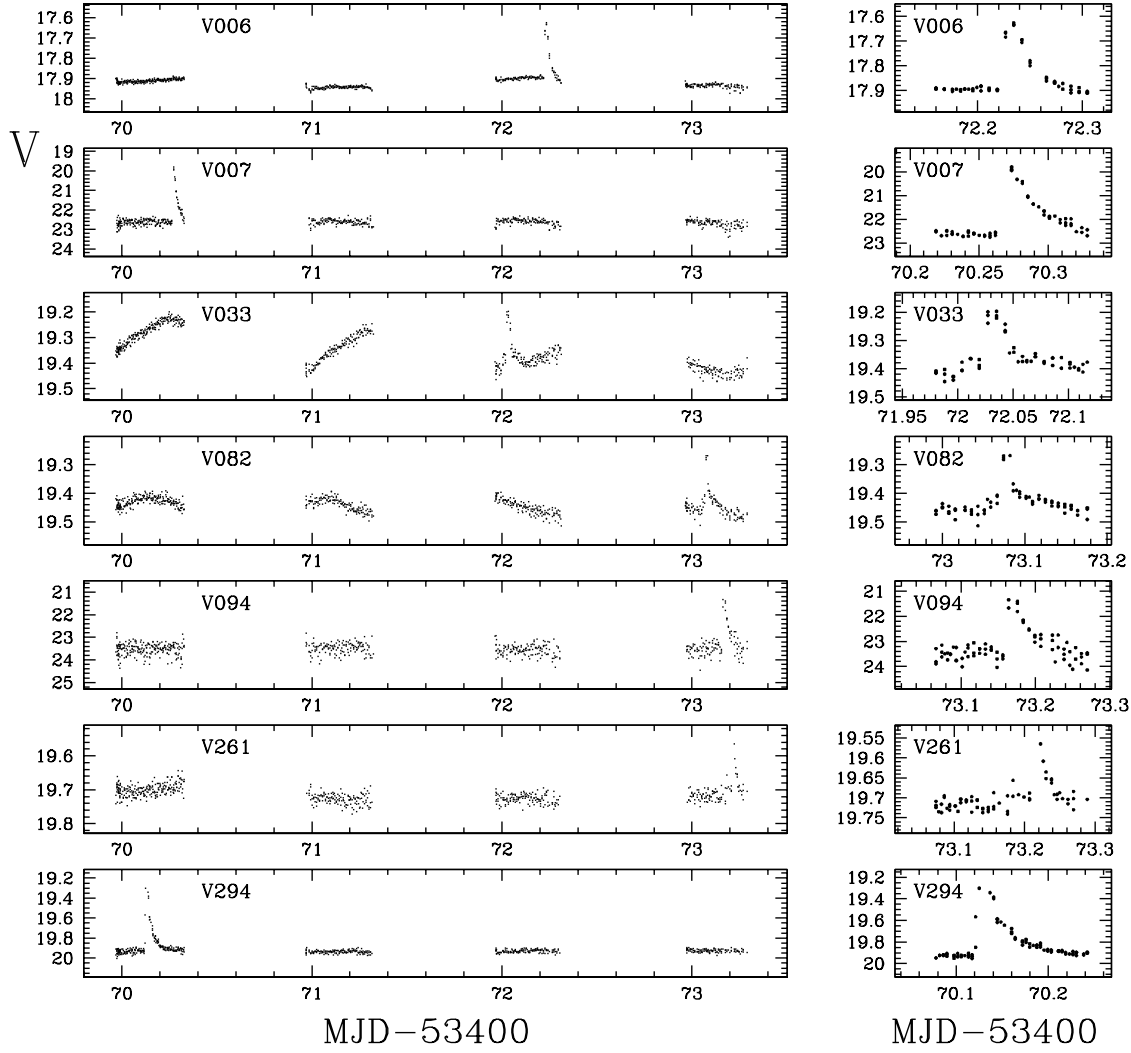
**Fig. 12.** Phased light curves for other pulsating variables with estimated periods (part 1 of 2). The identifications and periods in days are given for each object.



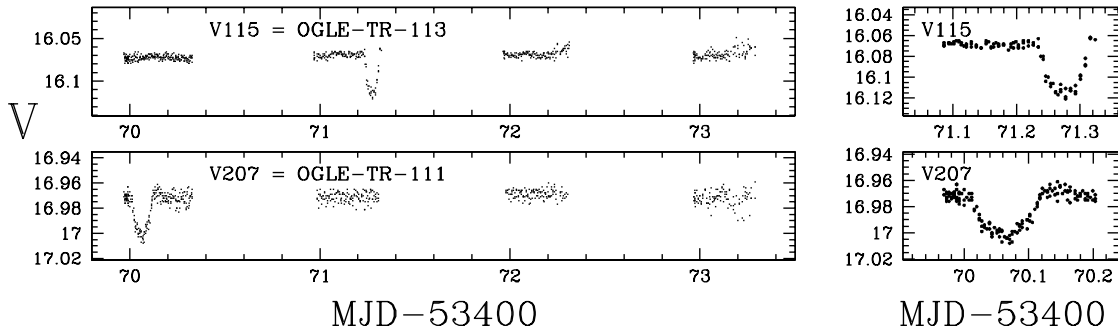
**Fig. 13.** Phased light curves for other pulsating variables with estimated periods (part 2 of 2).



**Fig. 14.** Light curves of other variable objects. Most of them are likely long-period variables.



**Fig. 15.** Stars with flares. Note the the object V033 is also a periodic (very likely pulsating) variable with  $P = 1.1625$  d for which phased light curve is illustrated in Fig. 12.



**Fig. 16.** Two planetary transits: V115 (OGLE-TR-113) and V207 (OGLE-TR-111).